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THERMOSCIENCES DIVISION

Final Technical Report

on

ADVANCED DIAGNOSTICS FOR REACTING FLOWS

Grant AFOSR 95-1-0041

Prepared for

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

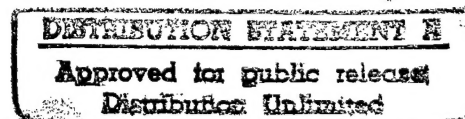
For the Period

November 1, 1994 to October 31, 1997

Submitted by

R.K. Hanson, Principal Investigator

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1.0 INTRODUCTION

Progress is reported for the past three years of a research program on advanced diagnostic techniques for combustion gases and plasmas. The techniques studied are based on laser spectroscopy, particularly spectrally-resolved absorption and laser-induced fluorescence. Laser sources include tunable cw diode lasers and tunable (or fixed-frequency) pulsed lasers. The cw lasers are spectrally narrow, allowing study of innovative techniques based on spectral lineshapes, while the pulsed lasers provide intense bursts of photons needed for techniques based on light-scattering phenomena. Accomplishments of note include: successful development of wavelength-multiplexing schemes which allow diode laser absorption measurements of multiple flow parameters along a common optical path; the first application of frequency-doubled diode lasers for combustion species measurements; establishment of a simple and sensitive means of imaging temperature in flows of air seeded with acetone; innovation and validation of a fluorescence-based plasma diagnostic for static pressure and kinetic temperature; and development and demonstration of a new class of sensors, based on multiplexed diode laser absorption, for near-real-time combustion control.

2.0 PROJECT SUMMARIES

Included in this section are summaries of work conducted in each of seven project areas. Additional details may be found in the publications listed in Sections 3.1 and 3.2. Reprints of these papers are available on request. Personnel involved in these projects are listed in Section 4.0.

2.1 Plasma Diagnostics

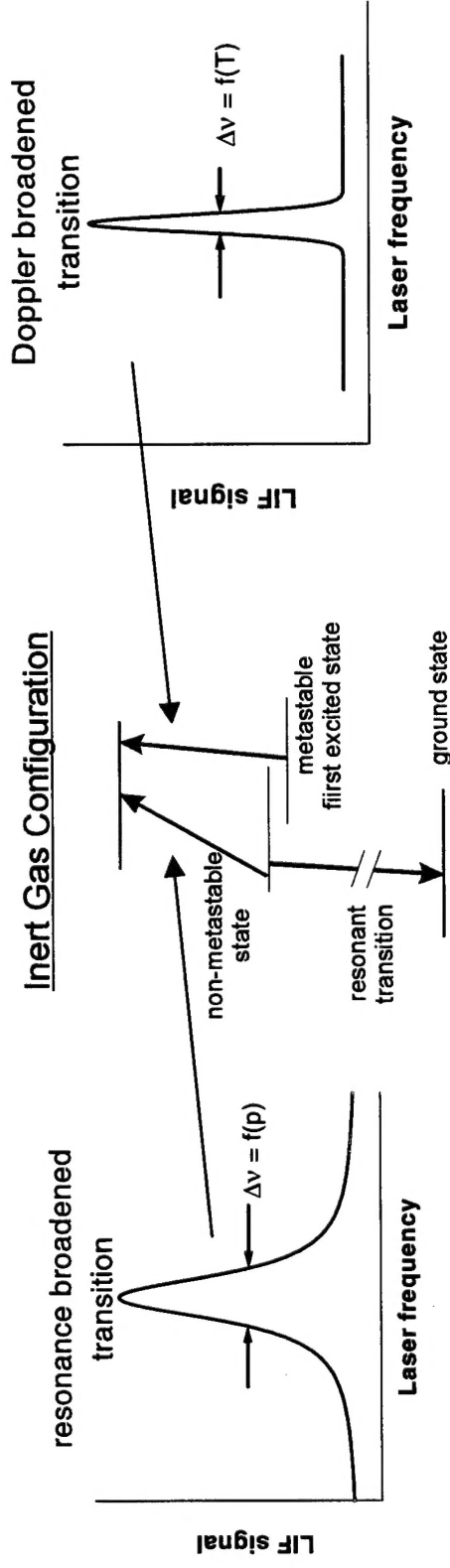
Over the three-year course of this program we continued to explore the use of cw semiconductor diode lasers as light sources for fluorescence diagnostics of temperature, number density and velocity in laboratory plasmas. This class of lasers is of high scientific interest owing to their unique ability to provide an economical source of rapidly tunable, narrow-linewidth, cw laser light in the visible and near-IR spectral regions. Owing to their rugged nature and compatibility with a rapidly growing range of fiberoptic components, these lasers also offer considerable promise for new diagnostic methods and for laser-based sensors in engineering systems, leading ultimately to new strategies for control of propulsion systems.

Our primary accomplishment was the development of a new laser-induced fluorescence (LIF) diagnostics strategy for sensing plasma temperature and pressure, shown schematically in Fig. 1. The concept involves probing a combination of excited-state transitions in an inert atomic species, with one transition involving a non-metastable lower state and the other involving an adjacent, metastable state. The basic idea is that the lineshape of the absorption transition involving the metastable state will be predominantly Doppler-broadened, and hence a simple function of the kinetic temperature of this species, while the lineshape for the absorption transition from the non-metastable state will be dominated by resonance broadening, and hence a simple function of the number density of the species. With the temperature known, the number density measurement may also be seen as a pressure measurement.

We have investigated this diagnostics concept in a simple low-pressure discharge, shown in Fig. 2, with the capability to vary the gaseous composition and pressure. The experimental arrangement is conventional for cw LIF measurements, other than the fact that two diode laser sources, one for each of the transitions monitored, are employed. Our studies have focused on xenon as the test gas, owing both to the current interest in xenon for ion thruster propulsion systems, and to the fact that xenon spectroscopy has not received much previous attention. Figure 3 provides an energy level diagram for xenon, and indicates the two 6s-6p transitions of interest at 823 nm (involving the metastable lower state) and 828nm (non-metastable state). As may be seen, the spectrum of xenon is complicated by the existence of several isotopes (nine stable isotopes including three with greater than 20% abundance) and the hyperfine splitting of most energy levels.

PLASMA PARAMETER MEASUREMENTS USING SPATIALLY RESOLVED FLUORESCENCE SPECTROSCOPY

- T and p from LIF probing of adjacent metastable and non-metastable states
- linewidth of Doppler broadened transition enables T_{kin} measurement
- linewidth of resonance broadened transition offers p measurement capability



- First application of diode lasers for Xe LIF
- Relevant to studies of electric propulsion devices

Fig. 1. Plasma diagnostic concept based on spectrally resolved fluorescence spectroscopy.

Experiments were conducted over a range of conditions in the low-pressure discharge in order to evaluate the diagnostics strategy for temperature and pressure. An example result, obtained using the 823 nm transition to infer kinetic temperature, is shown in Fig. 4. The relative positions and the relative intensities of the 21 hyperfine-split lines are indicated in the figure. Each of the 21 theoretical lines is individually broadened and the resulting intensities added to construct an excitation spectrum similar to the LIF data, with temperature as the only variable. The resulting temperature, 310K in this case, is in good agreement with expectation. Similar lineshape fits for the 828 nm transition allowed inference of the static pressure in the cell, and these data were found to agree well with the measure pressure. The only deficiency observed with the diagnostic method was that, at pressures above about 25 torr, the relationship between the resonance-broadened linewidth and pressure became slightly nonlinear. This is a result of incipient breakdown in the simple linear theory (for resonant-collision line broadening) which was used; an improved theory allowing for nonlinear contributions could be applied to correct for this minor effect.

In summary, we have developed a new plasma diagnostic strategy based on spectrally resolved LIF which offers the ability for nonintrusive measurements of two useful parameters, namely kinetic temperature and static pressure, with high spatial resolution. The use of diode laser excitation for such measurements implies that the diagnostic system can be cost effective and is also compatible with remote measurements through use of optical fibers. Further details of this work can be found in publications 12 and 24 in Sec. 3.1.

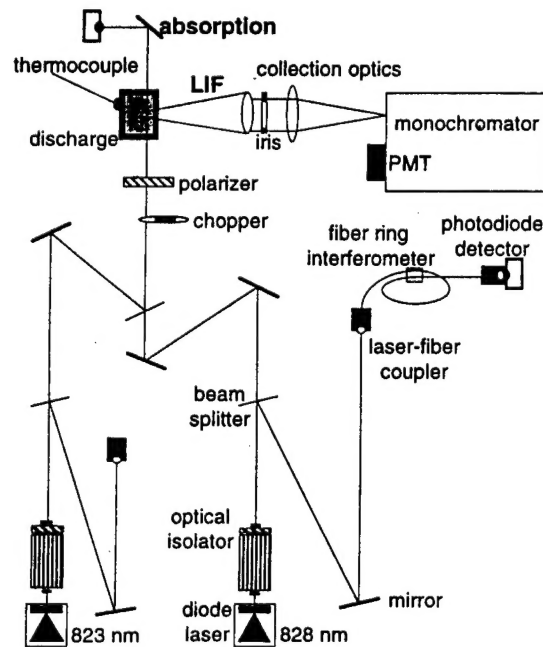


FIG. 2. Experimental setup.

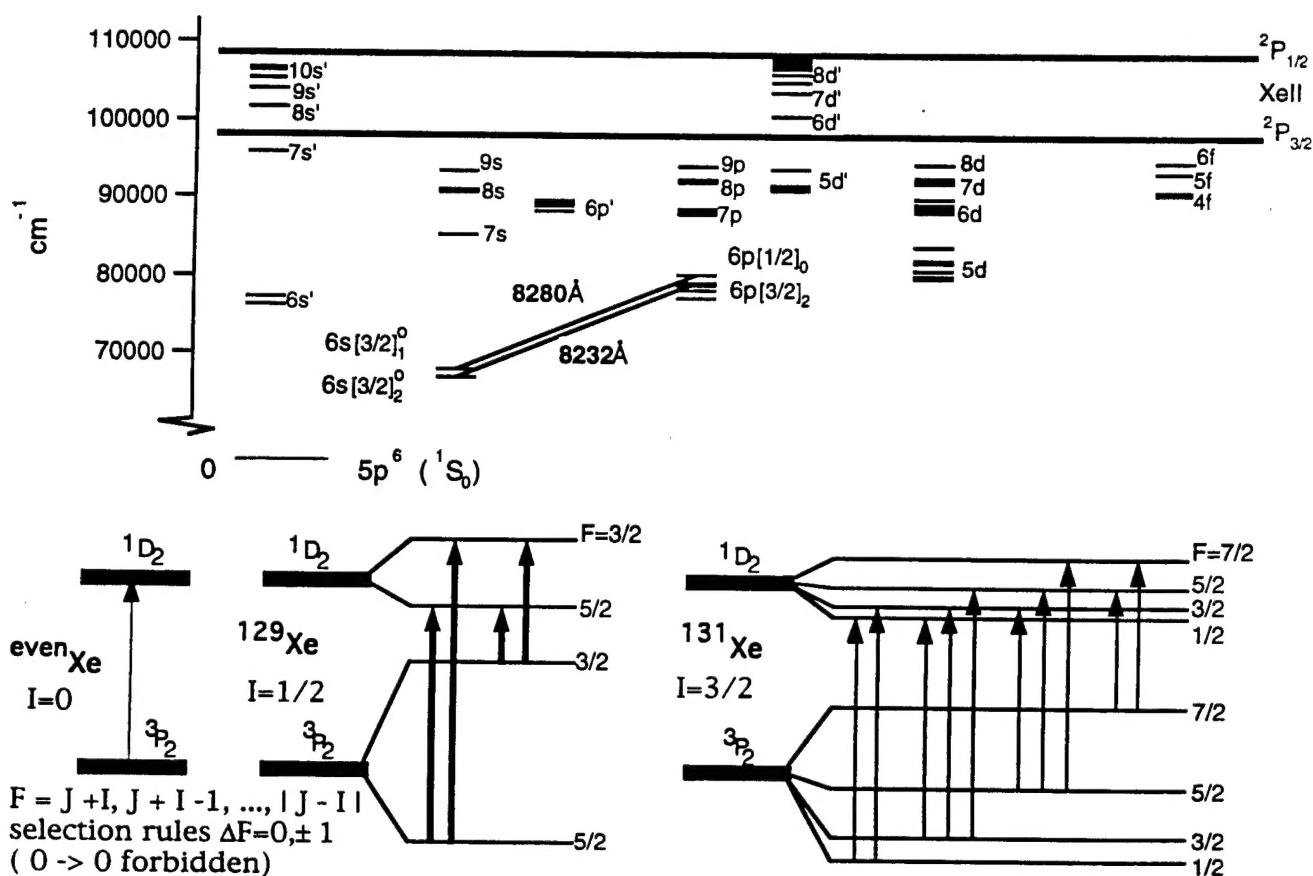


Fig. 3. Xenon energy level diagram. Nuclear spin splitting of the $6s[3/2]_0 \rightarrow 6p[3/2]_2$ ($^3P_2 - ^1D_2$) transition for even and odd (129 and 131 amu) atomic weights.

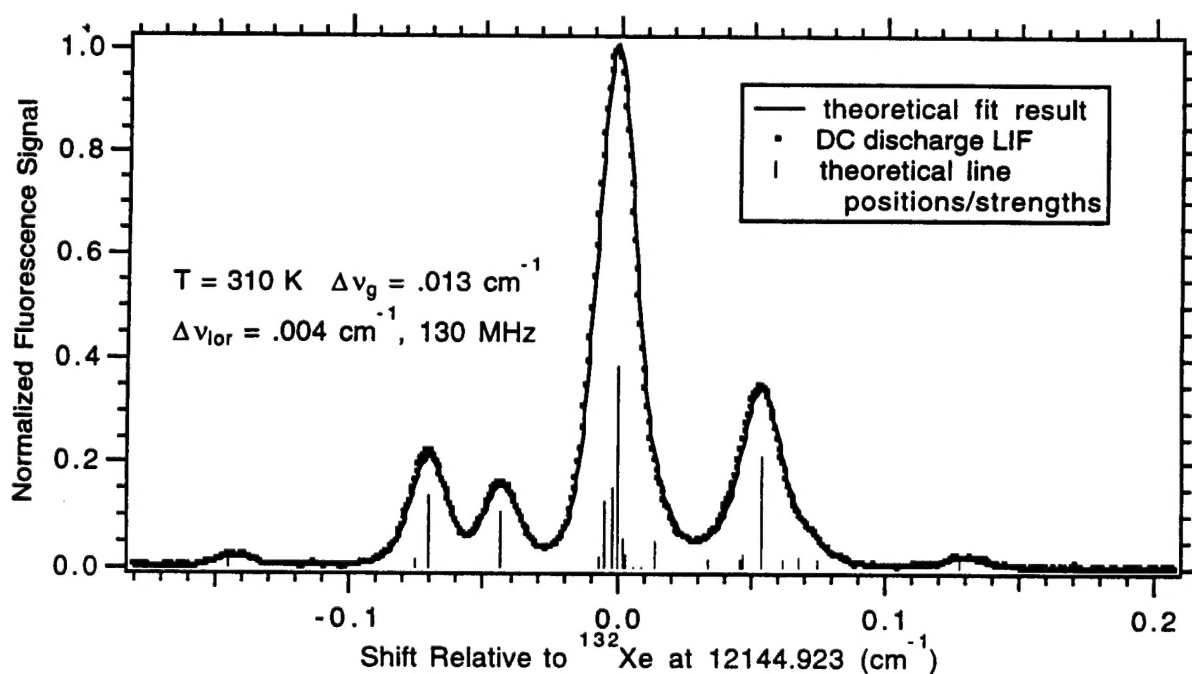


Fig. 4. Comparison of measured LIF $6s[3/2]_0 \rightarrow 6p[3/2]_2$ spectrum to calculated fit result

2.2 Diagnostics for High-Enthalpy Air

Atomic nitrogen and oxygen are important constituents in many high temperature environments such as in hypersonic air flows and propulsion plasmas. For example, in equilibrium air at 1 atm and 3500 K, the mole fraction of O-atoms exceeds that of molecular oxygen, and above about 7000 K, the atomic species N and O are the primary components of air. Gases at such high temperatures can have significant populations in excited electronic states, thereby suggesting the use of either laser absorption or laser-induced fluorescence to monitor gaseous properties through detection of the strong and optically accessible electronic transitions.

Semiconductor diode laser diagnostics have been developed capable of probing the electronically excited state transitions of atomic nitrogen and oxygen to determine both the kinetic temperature and the number density of the species in the absorbing states. Experiments were conducted behind reflected shock waves in a pressure driven shock tube using scanned-wavelength and fixed-wavelength strategies. The electronically excited transitions probed were at 821 nm for atomic nitrogen and at 777 nm for atomic oxygen.

The scanned-wavelength experiments allow determination of spectral lineshapes which contain important environmental information such as the kinetic temperature and the number density of the absorbing species. Fully-resolved spectral lineshapes for both nitrogen and oxygen atoms were recorded while scanning the diode laser at 6 to 8 kHz. Multiple lineshapes were obtained for the flowfield during the given test time. At high temperatures, the width of the line is dominated by Doppler broadening, and thus a measurement of linewidth is easily converted to a value for the translational (i.e. kinetic) temperature of the gas. The integrated area under the measured spectral absorption coefficient curve yields the number density of atoms in the absorbing (i.e. lower) state, from which we can invoke a Boltzmann distribution to infer an "electronic" or population temperature, assuming that the density of the species is known. It is important to note that the two temperatures inferred with these methods, i.e. the kinetic and electronic temperatures, may differ in gases at very high temperatures where radiative and collisional transfer processes are not in balance, and such difficulties motivate the need for diagnostics sensitive to these different temperatures in gases with very high enthalpies.

An energy level diagram for the relevant N-atom transitions, and a representative single-sweep data trace (converted from time to laser frequency) are shown in Fig. 5. The absorption data are converted through Beer's law to a plot of the spectral absorption coefficient and then best-fit with a Voigt profile. The kinetic and population temperatures obtained for this case (9000 versus 9300 K) are in close agreement as the flow has reached equilibrium during the test time available.

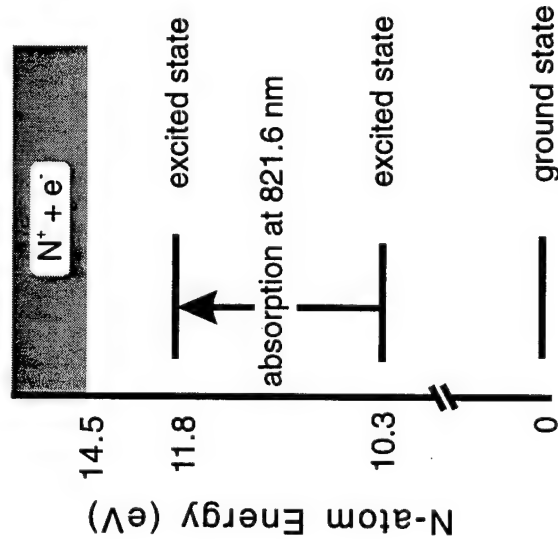
A plot of the comparison of kinetic, population, and calculated temperatures determined from atomic nitrogen absorption lineshapes for different experimental conditions is shown in Fig. 6. All three temperatures show good agreement with one another to within experimental error. This implies that the flow behind the reflected shock wave is in local thermodynamic equilibrium (LTE).

Further details of this work on diagnostics for gases at very high temperatures are available in the publications cited in Sec. 3.1 and 3.2.

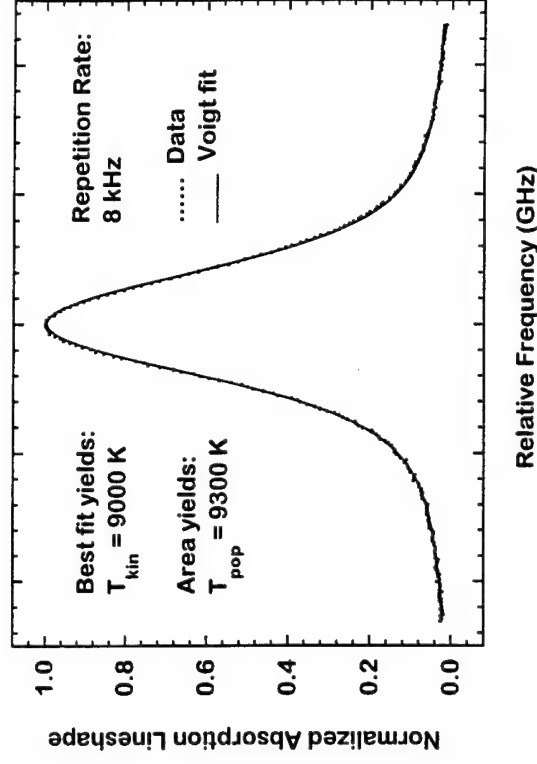
Diode Laser Absorption Diagnostic of Atomic Nitrogen for Hypersonic Flowfield and Plasmas

- High temperature measurements enabled by excited-state absorption

N-atom Excited State Absorption



Fast Repetitive Scans of N-atom Lineshape



- First use of excited N- and O- atom absorption in high enthalpy flows
- Kinetic and population temperatures determined simultaneously
- Well-suited for remote sensing using fiber optics
- Potential for monitoring velocity in high-speed flows

Figure 5. Diode laser lineshape measurements in high-temperature gases.

Fixed-frequency experiments were also conducted for electronically excited transitions of atomic nitrogen and oxygen. These measurements provide data on the continuous time-history of excited-state densities as the shock-heated gas undergoes dissociation, electronic excitation, ionization, and recombination. Such data will facilitate the development of kinetic models for the nonequilibrium behavior of air in hypersonic flows.

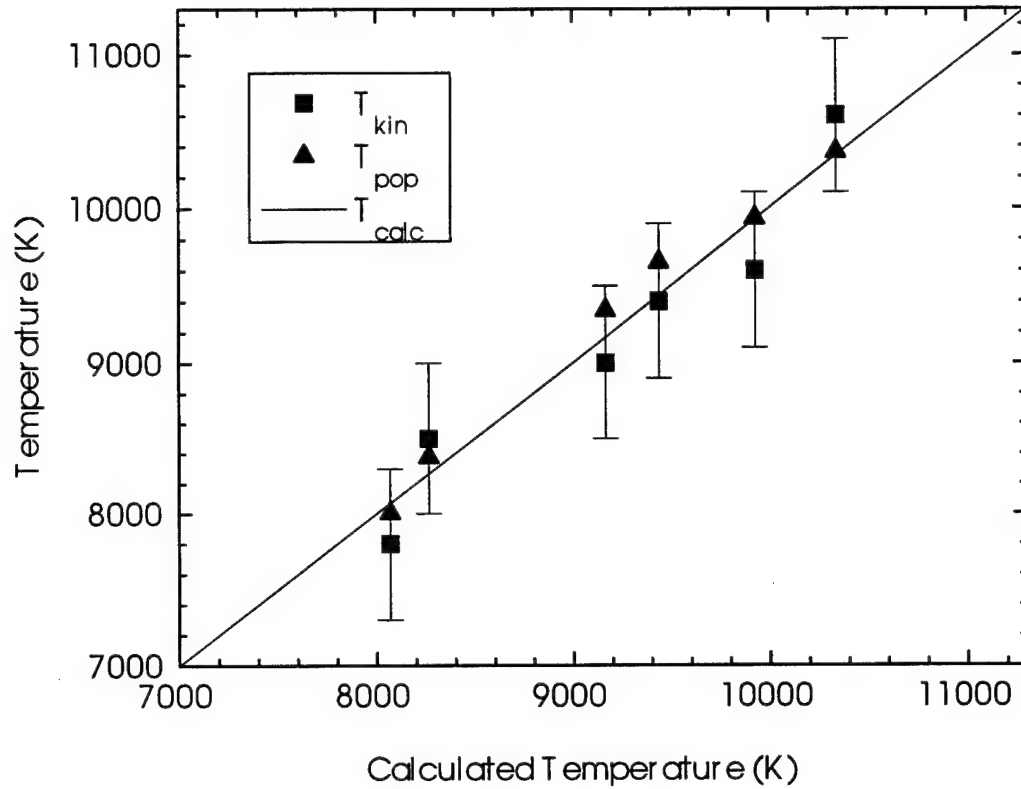


Figure 6. Comparison of kinetic, population, and calculated reflected-shock temperatures for N-atom absorption lineshape experiments.

2.3 Multiplexed Diode Laser Absorption

Early in this grant period we conceived a new approach for diode laser absorption based on the use of multiple laser sources, i.e. "wavelength-multiplexing". A multiplexed diode-laser sensor system is capable of monitoring several wavelength regions simultaneously, using either scanned- or fixed-wavelength laser-absorption spectroscopy techniques, thereby enabling measurement of multiple gasdynamic parameters along a common path. Thus far we have used this strategy to sensitively measure temperature, H_2O , O_2 and CH_4 in various combustion gases, high-speed flows and static cells, typically with either two or three diode lasers operating simultaneously.

Figure 7 (left side) schematically illustrates the generic setup used to record multiple gasdynamic parameters along a single path, based in this case on the simultaneous measurement of H_2O , O_2 and temperature. In the scanned-wavelength implementation of this method, two InGaAsP lasers were current tuned at a 2-kHz rate across H_2O vibrational transitions near 1343 and 1392 nm, while an AlGaAs laser was simultaneously scanned across an O_2 transition near 760 nm. Gas temperature was determined from the ratio of single-sweep integrated line intensities of H_2O . Species mole fractions (for H_2O and O_2) were determined from the measured integrated line intensities and inferred temperature. In the fixed-wavelength method, the wavelength of each laser was fixed near the peak of an absorption feature. Gas temperatures were inferred at a 1-MHz rate from the ratio of measured peak line intensities. The right side of Fig. 8 compares temperature measurements recorded in the post-flame gases of a premixed H_2 - O_2 flame and a heated cell. The excellent agreement between the laser-based measurements obtained using scanned- and fixed-wavelength methods with those recorded with thermocouples demonstrates the effectiveness of the multiplexed diode-laser sensor system and the potential for rapid, continuous measurements of gasdynamic parameters in flows with difficult optical access.

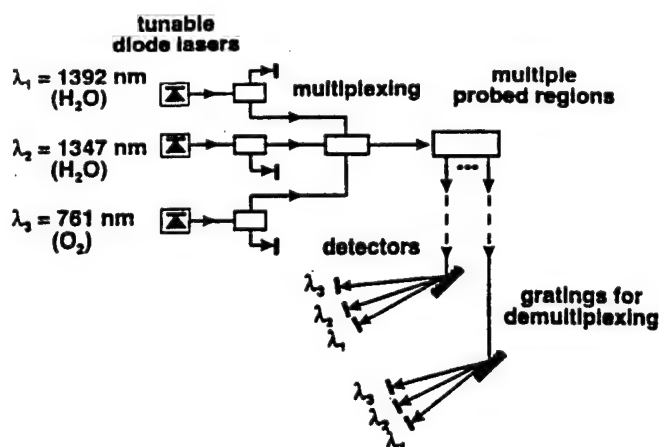


Fig. 7. Schematic for multiplexed diode-laser absorption diagnostic for simultaneous measurements of temperature, H_2O and O_2 .

Comparison of measured temperatures in a flame and a static cell

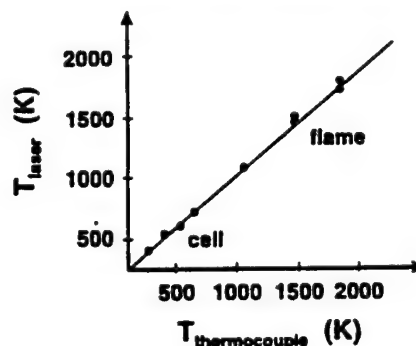


Fig. 8. Temperature results for multiplexed diode laser diagnostic.

2.4 Diagnostics for Combustion Sensing and Control

Over the past few years, significant advances have been made in our laboratory to develop multiplexed diode-laser sensors for combustion sensing and control. A multiplexed sensor system, comprised of multiple diode-laser sources, enables simultaneous monitoring of absorption at several wavelengths, thereby allowing simultaneous determination of multiple gasdynamic parameters and/or species concentrations. These measurements can be made remotely and at multiple locations through the use of fiber optics. Figure 9 illustrates possible applications to a gas turbine engine, where the sensor system could be applied for measurements of inlet mass flux, combustion efficiency, and thrust, as well as control of both combustion instabilities and the infrared signature. Accomplishments at Stanford have included air mass flux sensing in a supersonic stream by O_2 absorption, measurement of momentum flux (thrust) in a high-speed combustion flow via H_2O detection, simultaneous monitoring of H_2O , O_2 (or CH_4), and temperature in a benchtop combustor, and combustion control using temperature and H_2O concentration.

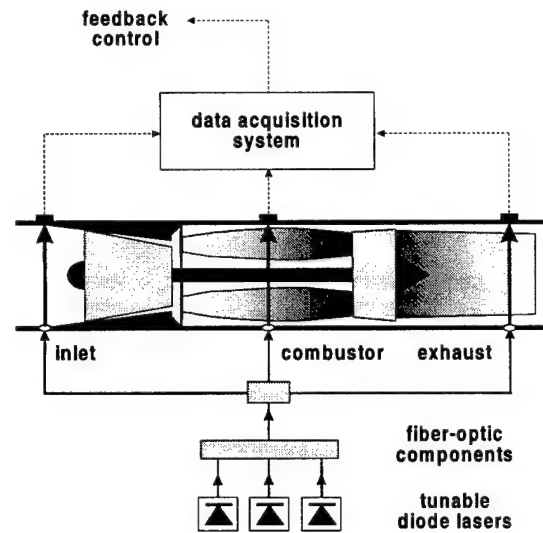


Fig. 9. Proposed application of sensor system to gas turbine combustor.

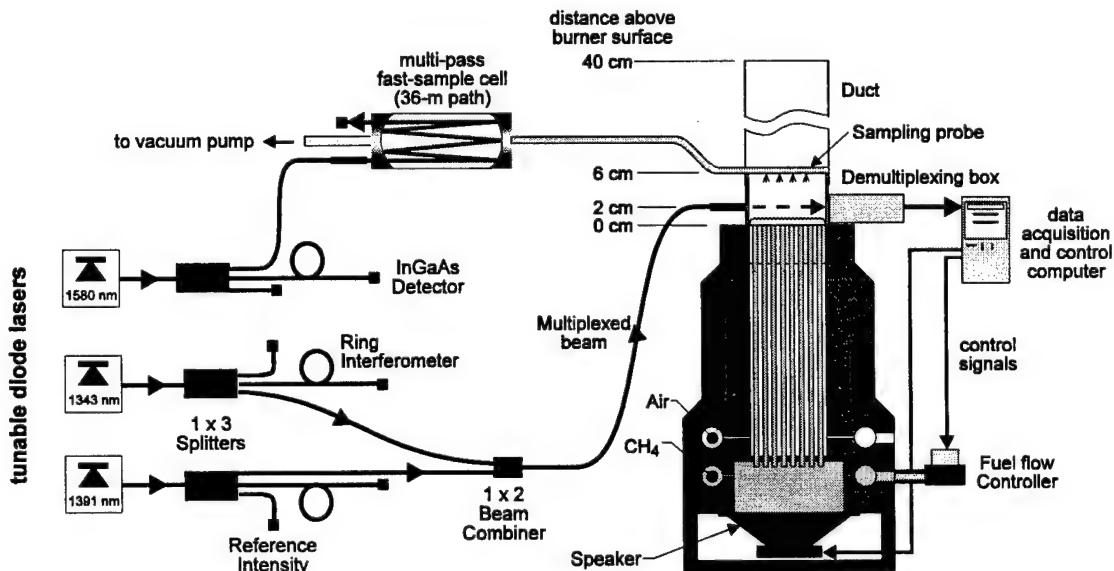


Fig. 10. Schematic diagram of the multiplexed diode-laser sensor for *in situ* and fast-sampling measurements.

Figure 10 illustrates the experimental arrangement used in recent work to investigate and develop new sensing concepts for both *in situ* measurements of temperature, H_2O , and CO_2

concentration, as well as fast sampling measurements of important pollutants such as CO and NO_x. The *in situ* diagnostic, using diode lasers tuned to absorption features in the near IR (1.4 μ m) absorption spectrum of water vapor, allowed simultaneous measurements of temperature and H₂O concentration from the ratio and absolute magnitude of the absorption signals. These near-real-time measurements (currently conducted at a repetition rate of 3 kHz) have been used to maintain desired temperature set points (Figure 11), and minimize temperature fluctuations (Figure 12) in a benchtop combustor.

This capability was recently utilized in the active control system for a prototype shipboard waste incinerator being developed at the Naval Air Warfare Center (NAWC), China

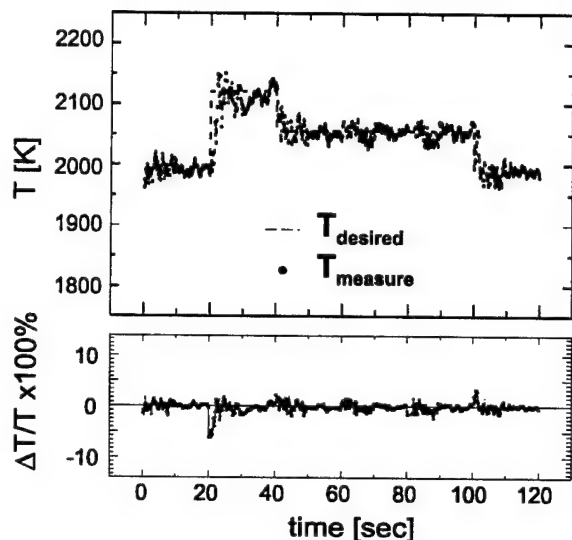


Fig. 11. Comparison of measured and set-point temperatures with control system in operation. NAWC (50-kW combustor) by Stanford researchers. A closed-loop control system used T_{rms} values to optimize the timing of the fuel injection.

Lake, CA (Figure 13). The NAWC researchers (T.P. Parr, E.J. Gutmark, K.J. Wilson, D.M. Hanson-Parr, K. Yu, R.A. Smith, and K.C. Schadow) chose to use pulsed air injection to maintain the compactness and robustness required for successful application of this incineration system aboard Naval ships. The air modulation led to coherent air vortices at the dump plane of the combustor. By precise timing of the combustible waste (fuel) injection into these vortices, a high degree of mixing was obtained, reducing the emission of CO and other harmful pollutants to near equilibrium levels. Proper injection resulted in large coherent temperature oscillations at the forcing frequency (T_{rms}), large temporally-averaged H₂O concentration, and low levels of CO, as indicated in Figure 14, measured at

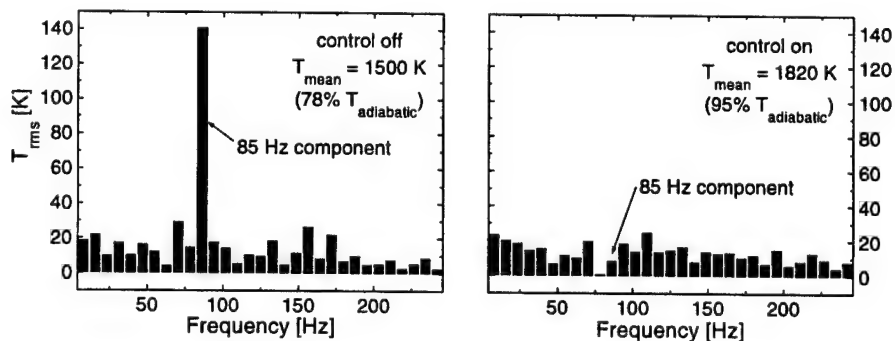


Fig. 12. Measured power spectra before (left) and after (right) active control was initiated on the ducted burner.

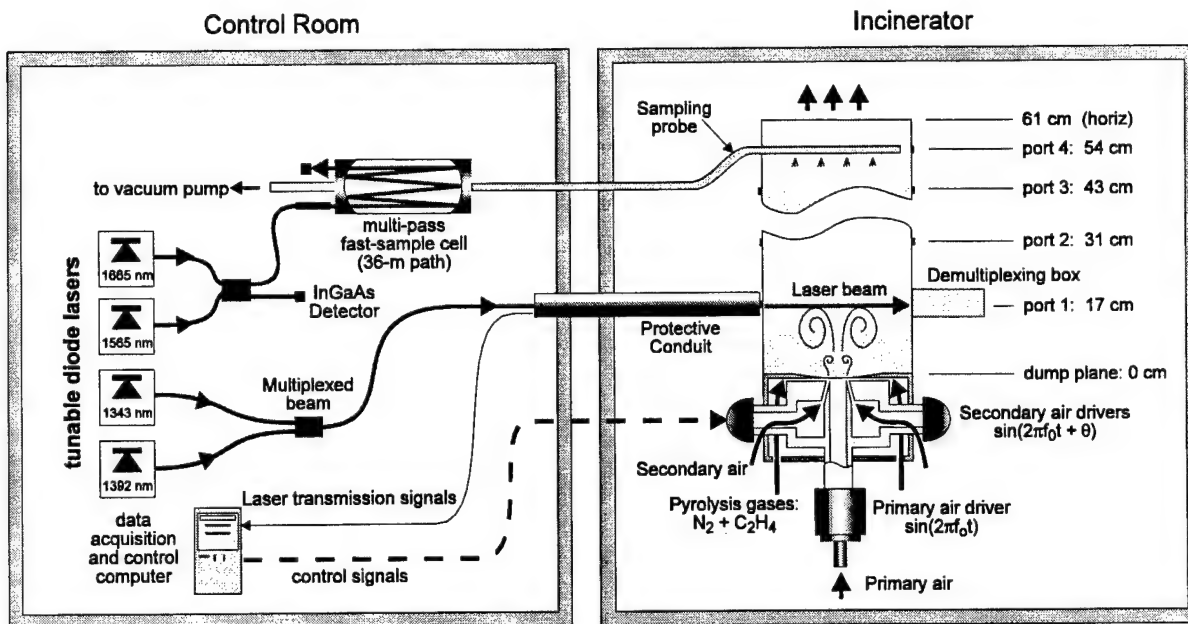


Fig. 13 Schematic diagram of the multiplexed sensor applied to the 50-kW facility at NAWC.

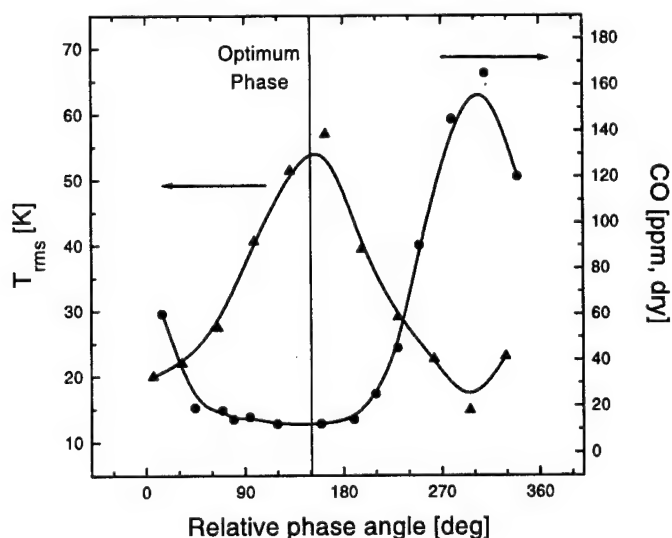


Fig. 14. Variation of T_{rms} (left axis) measured at $x/d=4.4$ and CO concentration of gases sampled at $x/d=14.1$ (right axis) with phase angle in 50-kW combustor at NAWC. Primary air jet dia., $d = 3.84$ cm.

time scales as short as 100 ms, and excellent overall performance, as evident by the near equilibrium H_2O concentration, over somewhat longer time scales (~ 10 sec). Further details of this diode-laser sensor research may be found in paper 14 in Sec. 3.1, and papers 14-17 and 28-30 in Sec. 3.2.

Recent work has involved improving the bandwidth of the closed-loop system and exploring new control strategies in a 5-kW model of the NAWC combustor. A sample result, shown in Figure 15, illustrates the ability of the closed-loop system to rapidly vary the amplitude and phase of the fuel injection (relative to the air injection) to optimize the coherence of the temperature oscillations (maximum T_{rms}). Concurrently, the H_2O concentration at the measurement location was maximized by lowering the allowable forcing amplitude (steps in lower frame). This combined strategy resulted in efficient, premixed combustion, as evident from the lack of soot luminosity, over

The successful demonstration of rapid closed-loop control in realistic combustion systems illustrates the high potential of diode-laser absorption sensors for improved measurement and control of combustion and propulsion systems, including applications that require remote and non-intrusive monitoring. These sensors should prove useful for both ground-based and flight-based systems.

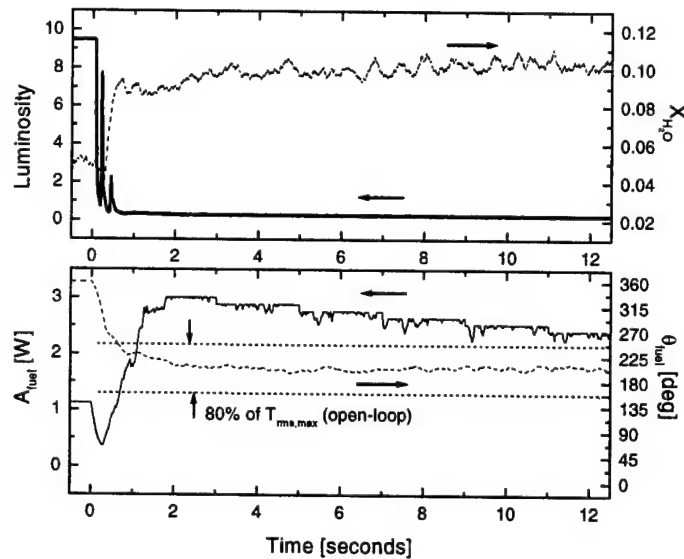


Fig 15. Overall time response of control strategy which simultaneously varied phase (bottom frame, right axis) and amplitude (bottom frame, left axis) to maximize X_{H_2O} and T_{rms} . Measured in 5-kW Stanford facility at $x/d=2.0$, where $d=2.1$ cm.

2.5 PLIF of Acetone for Temperature Imaging

An effort combining fundamental photophysical studies and modeling has led to the development of acetone PLIF temperature imaging as an immediately applicable diagnostic technique for flows of interest to the combustion community. The comparative ease of application of acetone PLIF, and the large and potentially easily interpretable signals that result, has made it popular in recent years for measurements of concentration, especially as an indicator of mixing. Recognition, however, of the significant dependences of fluorescence signal on temperature and excitation wavelength (and the weak dependence on pressure), prompted experimental studies (see papers 21 and 26 in Sec. 3-1) to characterize these effects. The results of these studies enabled the development of single- and dual-excitation-wavelength strategies for temperature measurement with acetone PLIF (paper 21). Modeling of acetone fluorescence (paper 26) in conjunction with the photophysics experiments has broadened acetone PLIF diagnostic capability to include quantitative dual-parameter measurement (*e.g.*, temperature and mixture fraction, or temperature and pressure) in various flowfields.

The transitions in the acetone molecule that make PLIF viable and attractive are shown in Fig. 16. Ultraviolet laser excitation pumps molecules from the ground singlet state to the first excited singlet, with subsequent fluorescence in the visible back to the ground state, which can be detected with an unintensified CCD camera. Notably, the fluorescence efficiency is limited by a rapid intersystem crossing to the non-fluorescing excited triplet state, rather than by collisional interactions with other molecules, resulting in a more easily interpretable fluorescence signal. Temperature and wavelength dependences in the fluorescence signal appear through the excitation efficiency (described by the absorption cross-section, σ) and the fluorescence efficiency (described by the fluorescence quantum yield, ϕ), with an additional inverse temperature dependence in the number of acetone molecules found in a given volume (the number density, n_{acetone}). Analysis of these processes revealed that a straightforward single-excitation-wavelength temperature measurement strategy would be effective in conditions of uniform pressure and acetone seeding, while a dual-wavelength approach would be useful when these conditions were not met. The achievable temperature sensitivities for idealized experimental conditions are shown in Fig. 17 for the two approaches using candidate excitation wavelengths.

The effectiveness of the single-wavelength technique for imaging of temperature to within several degrees Kelvin is demonstrated in Figs. 18 and 19. For the low speed flow of acetone-seeded air over a heated cylinder shown in Fig. 18, the excellent single-shot sensitivity of the technique is highlighted by a banded, repeating color table. Laser excitation is at 248 nm – 40 mJ in a 0.5 mm thick sheet. The ability of acetone PLIF to resolve instantaneous temperature structure is shown in Fig. 19, for 266 nm excitation. The jet-in-crossflow pictured has both streams uniformly seeded with acetone. The temperature variations associated with jet instabilities are evident at a Reynolds number of 100.

Preliminary validations of dual-wavelength imaging in steady flows with nonuniform acetone seeding have been followed by applications in turbulent flowfields that require near-simultaneous detection of fluorescence resulting from successive excitation at 248 and 308 nm. In such conditions, fluorescence modeling (paper 26) indicates that the dual-wavelength

approach offers the potential for simultaneous measurement of two parameters. This might, for instance, involve simultaneous imaging of pressure and temperature in a supersonic expansion, or temperature and mixture fraction in an optically-accessible engine cylinder. A laboratory demonstration of the technique has involved the use of a CCD camera with interline transfer architecture (on loan from Prof. Mungal's research group) to record separate fluorescence images of a heated, turbulent jet from respective excitation pulses at 308 and 248 nm, with as little as 1 microsecond separation between frames.

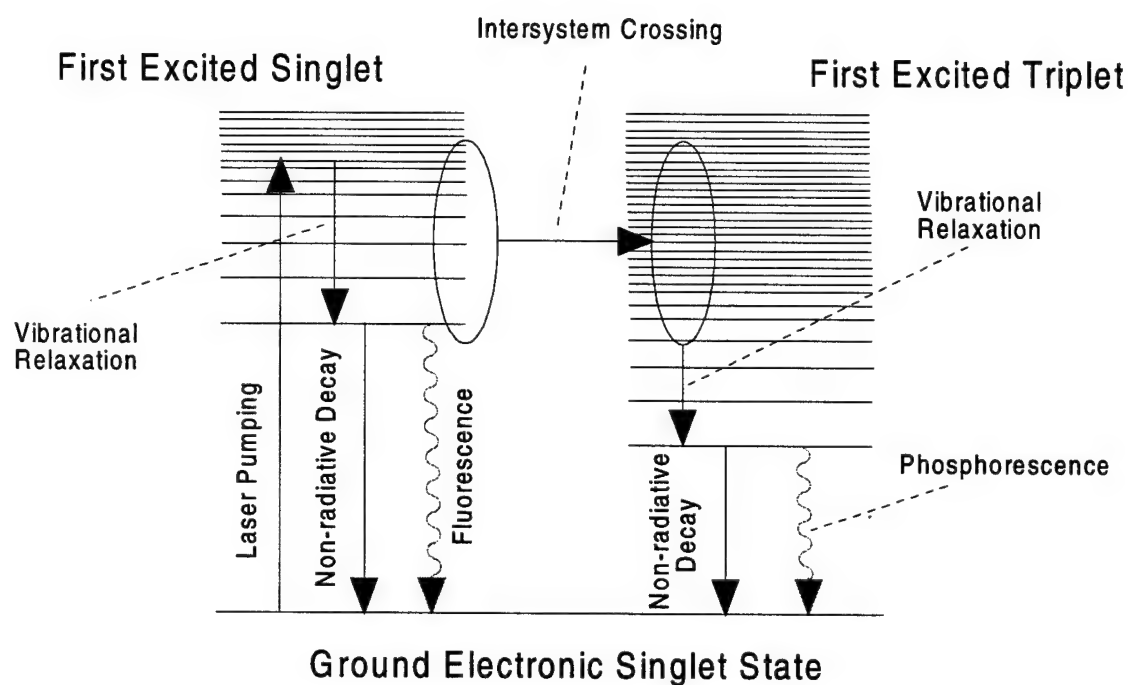


Figure 16. Energy level diagram for acetone.

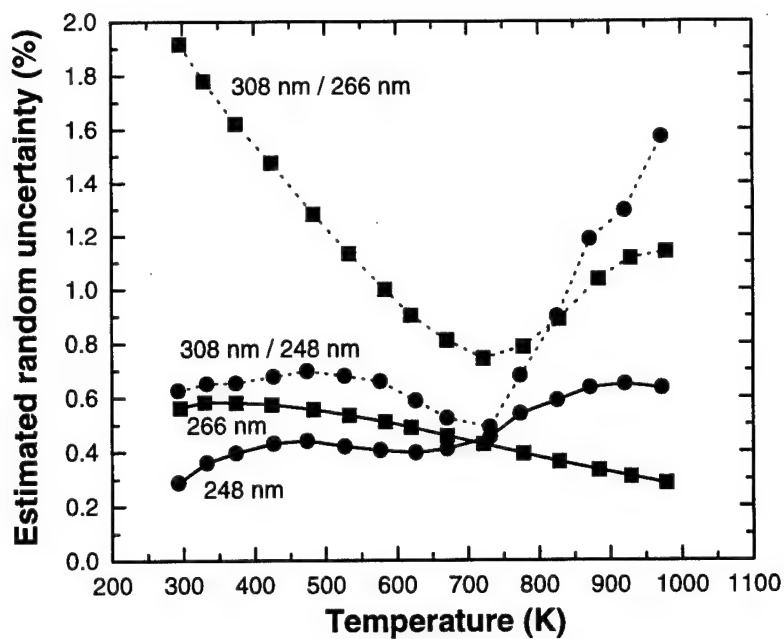


Figure 17. Estimated random uncertainties attainable with different diagnostic approaches for a shot-noise-limited experiment: solid curves, single-wavelength technique; dotted curves, dual-wavelength technique.

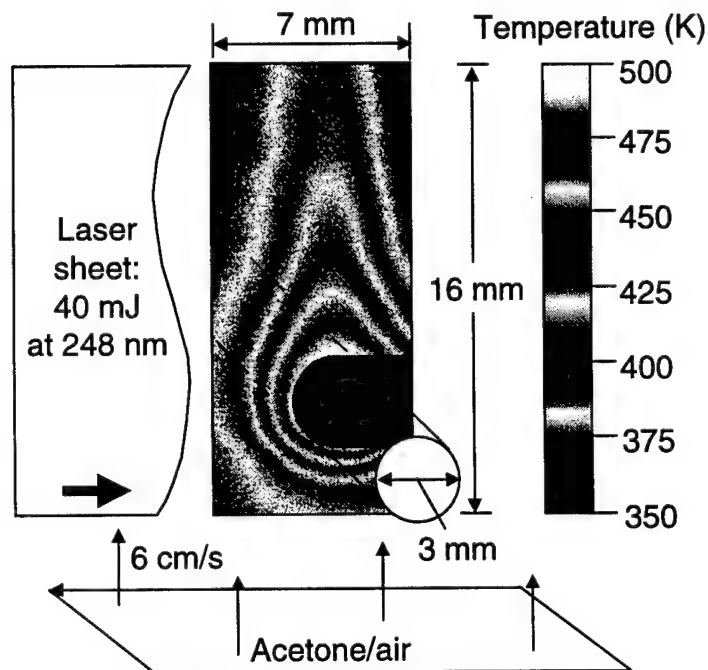


Figure 18. Single-shot temperature image in a heated cylinder flow, generated with the single-wavelength technique using 248 nm excitation.

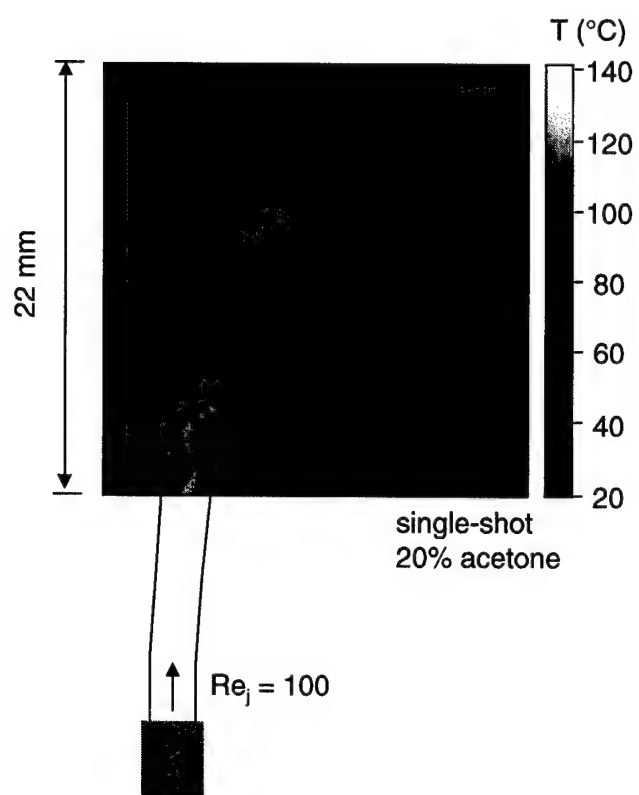


Figure 19. Single-shot temperature image of an unstable jet in crossflow acquired using 266 nm excitation.

2.6 Frequency-Doubled Diode Laser Diagnostic

The commercial availability of diode lasers has been limited to distinct spectral windows within the overall spectral range between 630 nm to 2.0 microns. As a consequence, various species that are important for combustion and propulsion monitoring and control applications remain inaccessible to absorption measurements. Recent development in quasi-phase-matched second harmonic generation (QPM-SHG) using LiNbO_3 waveguides has enabled both high nonlinear optical conversion efficiency and the capability of operating at any desired wavelength within the transparency range of the crystal, ideal for diode-laser applications. We have collaborated with the Applied Physics Department at Stanford to access a prototype diode-laser system generating approximately 100 nW of tunable output near 394.5 nm from a 8 mW external cavity diode laser near 789 nm. The newly available wavelength region enables access to atomic transitions of aluminum and gallium as well as to ro-vibronic transitions of NO_2 , an important combustion-generated pollutant. We conducted NO_2 absorption experiments using the prototype diode laser system near 394.5 nm and a diode laser near 670 nm, which is the shortest wavelength at which we have been able to obtain sustained, single-mode output using commercially available tunable diode lasers. The results obtained demonstrate the utility of near-UV diode-laser systems for sensitive measurements of NO_2 over a range of temperatures (296 K to 774 K) and total pressures (0.024 atm to 1 atm).

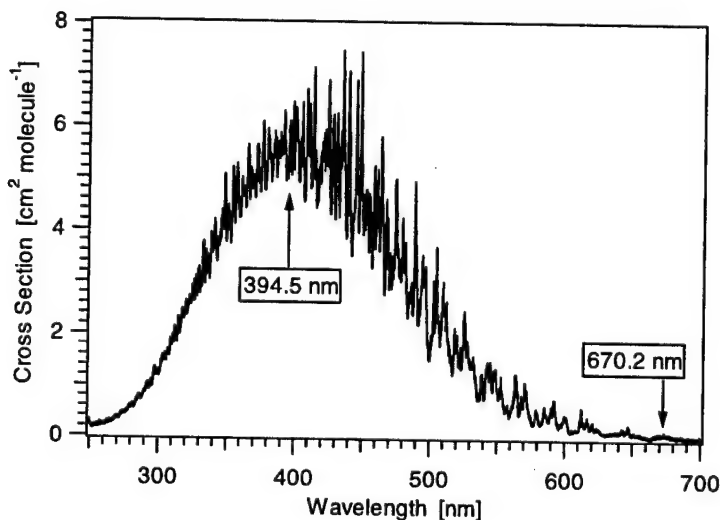
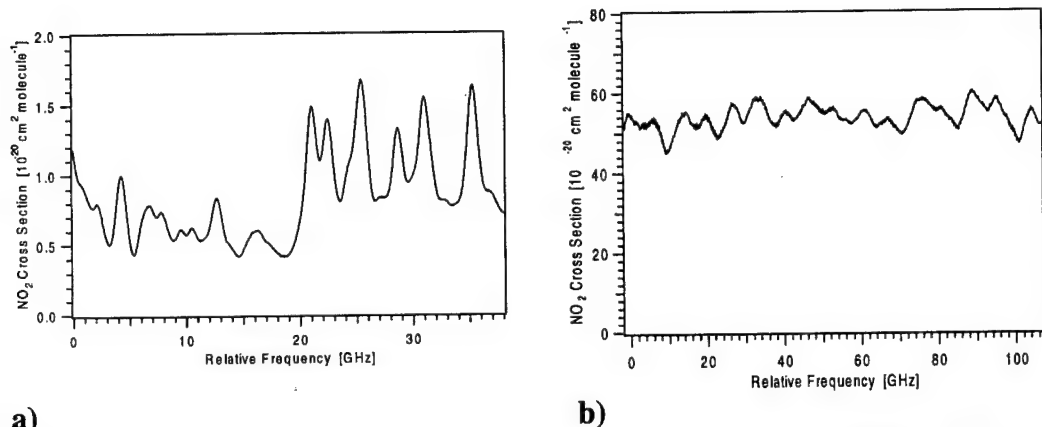


Fig. 20. Room temperature absorption spectra of NO_2 between 250 nm and 700 nm.

Figure 20 shows the room temperature absorption spectrum of NO_2 between 250 nm and 700 nm, highlighting the potentially increased sensitivity near 400 nm over measurements near 630 nm. We performed NO_2 absorption measurements at the two indicated spectral regions at various temperatures (296 K to 774 K) and pressures (0.024 atm to 1 atm). Figure 21a shows the measured high-resolution spectra of NO_2 from 670.184 nm to 670.241 nm at 296 K (0.055 atm, 1.96% NO_2 in Ar).



a) **Fig. 21a.** High-resolution absorption spectra of NO₂ referenced to 670.241 nm (296 K, 0.055 atm, 1.96% NO₂ in Ar). **Fig. 21b.** High resolution absorption spectra of NO₂ referenced to 394.548 nm (300 K, 0.14 atm, 1.91% NO₂ in Ar)

By contrast, Fig. 21b shows the measured NO₂ absorption spectra from 394.493 to 394.548 nm at 300 K (0.14 atm, 1.91% NO₂ in Ar). The average measured cross section near 394.5 nm exceeds those obtained near 670.2 nm by a factor of 60 at room temperature. Fig. 22 shows the variation of the absorption coefficients in the two spectral regions as a function of temperature. The NO₂ absorption coefficient near 394.5 nm exceeds those near 670.2 nm by approximately a factor of 25 over the entire temperature range between 298-500 K, thereby confirming the merit of near-UV wavelengths for enhanced NO₂ detection. In summary, NO₂ detectivities of 5 ppm (670.2 nm) and 0.1 ppm (394.5 nm) are achievable in a 10-cm path, based on the measured minimum detectable absorbance of 1.1×10^{-4} (20-kHz bandwidth (-3dB), 1-ms measurement time). Further details of this work may be found in publication paper 29 in section 3.1.

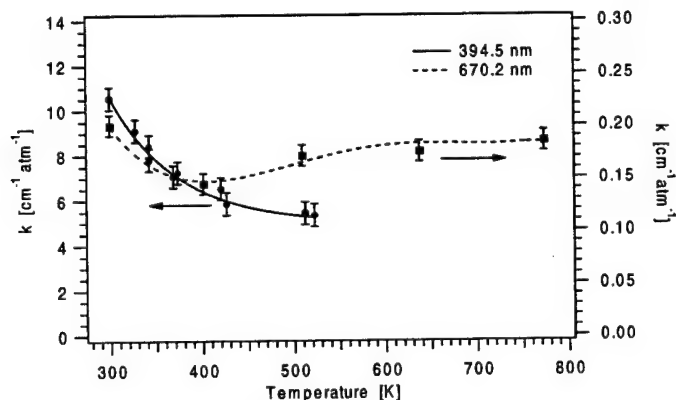


Fig. 22. Average absorption coefficients in the two spectral regions near 394.5 nm and 670.2 nm as a function of temperature.

The potential for sub-ppm NO₂ detection of frequency-doubled diode laser sources suggests that this diagnostic strategy will find important applications in combustion development and emissions monitoring applications. Further, through use of fiberoptic transmission, it will be possible to monitor NO₂ at multiple locations using a single laser source.

2.7 Diagnostics for High-Pressure Gases

Progress has been made on two projects to develop high-pressure laser diagnostics. The first program, an extension of work conducted previously for NASA-Lewis, aimed at PLIF measurements of NO and O₂ in the post-flame region of a high-pressure, lean-burning combustor. The problem to be resolved is that the spectra of NO and O₂ are highly overlapped in the spectral region (near 225 nm) best suited for measuring low levels of NO. The problem is seriously exacerbated by collision broadening of NO and O₂ spectral features at pressures of interest (10-50 atm) in high-pressure combustors and the fact that the concentrations of NO (10-100 ppm) are much smaller than the O₂ concentrations (10%). We have assembled a computer code incorporating the latest information on line positions, strengths and shapes (including pressure shifts), and have used the code to simulate absorption and fluorescence spectra for a variety of excitation and detection strategies. One attractive approach involves detection of the PLIF signal in two (or three) spectral channels following excitation at the single wavelength. Our simulations indicate that this approach can allow simultaneous monitoring of NO, O₂ and temperature. Further work on this topic is planned as part of a new grant from AFOSR.

The second project was focused on monitoring H₂O and temperature at high pressures using diode laser absorption. A critical element of this work was assembly of a code for calculations of water vapor spectra over a wide range of conditions. Example calculation of H₂O spectra for representative conditions of interest are shown in Fig. 23 which documents the role of pressure broadening, namely to eliminate regions of negligible absorption for pressures of 5 atm and higher. The latter finding invalidates the most common diode laser absorption strategy, which utilizes wavelength-scanning to record the full shape of isolated transitions.

As a replacement for the scanned-wavelength technique, we expect to utilize multiple laser sources fixed at selected wavelengths (i.e., fixed-wavelength technique) to monitor H₂O in high pressure environments. The water vapor code has been exercised to identify optimum wavelength pairs which can be used to measure temperature (through the ratio of absorption) in cases where pressure is known, and optimized candidates for a third wavelength have been found for measurement of pressure for the general case of simultaneous monitoring of temperature, water vapor concentration and pressure. Experiments have been performed at pressures up to 20 atm and temperatures up to 473 K to verify the high pressure spectral code. Experiments in a shock tube are currently planned to verify the code at pressures up to 50 atm and temperatures up to 1500 K.

In the process of this research effort, a comprehensive understanding of line shape phenomena that become important at high pressures has been developed. Both the impact and additive approximations conventionally employed in modeling line shapes may break down at high pressures. We have shown that the impact approximation can be used to accurately model regions of the H₂O line shape near the line center at high pressures. The use of the additive approximation in the modeling of H₂O absorption features has been validated experimentally for number densities up to 18 Amagat. Shown in Fig. 24 are the comparisons between the recorded data, at 473 K, and the simulations performed with line shapes based on the impact (Voigt) and additive approximations. Details of this work can be found in paper 25 in Sec. 3.1.

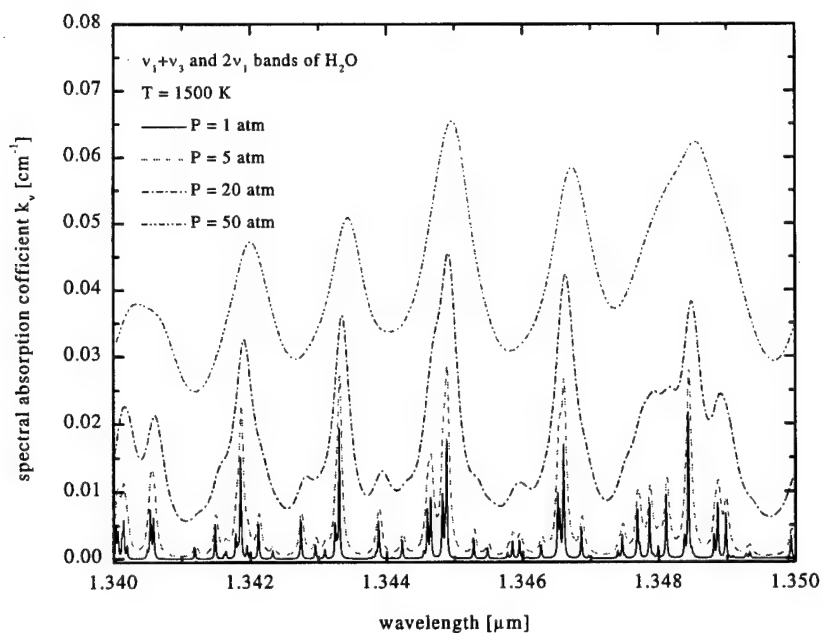


Fig. 23. Calculated absorption spectra of H₂O at various pressures for a mixture of 20% H₂O, 80% N₂ at 1500 K. The increasing overlap of spectral features results from collisional broadening effects at high pressures and its typical at all wavelengths.

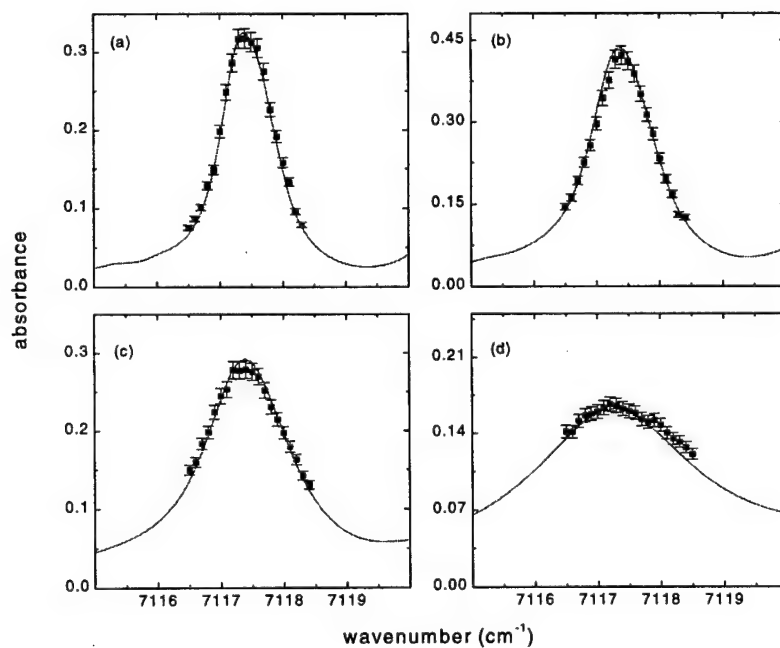


Fig. 24. Comparison between the recorded data and the simulation using line shapes based on the impact and additive approximations (solid line) at 473 K. The corresponding total pressures and the number densities are: a) 5.52 atm, 3.19 Amagat; b) 7.49 atm, 4.34 Amagat; c) 10.89 atm, 6.31 Amagat; d) 22.90 atm, 13.3 Amagat.

3.0 PUBLICATIONS AND PRESENTATIONS

This work has resulted in a substantial number of refereed publications, technical reports and presentations, as documented below. Copies of these papers and reports may be obtained on request to the Principal Investigator, Professor Hanson.

3.1 Refereed Publications (11/94 – 10/97)

1. M.P. Arroyo, T.P. Birbeck, D.S. Baer and R.K. Hanson, "Dual Diode-Laser Fiber-Optic Diagnostic for Water Vapor Measurements," *Optics Letters* **19**, 1091-1093 (1994).
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4. B.K. McMillin, J.M. Seitzman and R.K. Hanson, "Comparison of NO and OH PLIF Temperature Measurements in a Scramjet Model Flowfield," *AIAA J.* **32**, 1945-1952 (1994).
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8. H.A. Chang, D.S. Baer and R.K. Hanson, "Semiconductor Laser Diagnostics for Simultaneous Determination of Kinetic and Population Temperatures in High-Enthalpy Flows," in *Shock Waves @ Marseilles II*, Springer-Verlag, 1995, pp. 33-36.
9. R.K. Hanson, "The Role of Lasers in Shock Tube Studies of Chemical Kinetics," in *Shock Waves @ Marseilles II*, Springer-Verlag, 1995, pp. 7-13.
10. J.G. Liebeskind, R.K. Hanson and M.A. Cappelli, "Experimental Investigation of Velocity Slip Near an Arcjet Exit Plane," *AIAA J.* **33**, No. 2, 373-375 (1995).
11. D.S. Baer, V. Nagali, E.R. Furlong, R.K. Hanson and M.E. Newfield, "Scanned- and Fixed-Wavelength Absorption Diagnostics for Combustion Measurements using Multiplexed Diode-Laser Sensor System," *AIAA J.* **34**, 489-493 (1996).
12. R.J. Cedolin, R.K. Hanson and M.A. Cappelli, "Laser-Induced Fluorescence Measurements of Resonance Broadening in Xenon," *Phys. Rev. A*, **54**, 335-342 (1996).

13. D.F. Davidson and R.K. Hanson, "Real Gas Corrections in Shock Tube Studies at High Pressures," *Israeli J. Chemistry* **36**, 321-326 (1996).
14. E.R. Furlong, D.S. Baer and R.K. Hanson, "Combustion Control and Monitoring using a Multiplexed Diode-Laser Sensor System," 26th Symposium (International) on Combustion, The Combustion Inst., Pittsburgh, 1996, pp.2851-2858.
15. T.C. Island, B.J. Patrie, M.G. Mungal and R.K. Hanson, "Instantaneous Three-Dimensional Flow Visualization of a Supersonic Mixing Layer," *Experiments in Fluids* **20**, 249-256 (1996).
- J.D. Mertens and R.K. Hanson, "A Shock Tube Study of $H + HNCO \rightarrow H_2 + NCO$ and the Thermal Decomposition of NCO ," 26th Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, 1996, pp 551-558.
16. V. Nagali, S.I. Chou, D.S. Baer, R.K. Hanson and J. Segall, "Tunable Diode Laser Absorption Measurements of Methane at Elevated Temperatures," *Applied Optics*, **35**, 4026-4032 (1996).
17. J.L. Palmer and R.K. Hanson, "Temperature Imaging in a Supersonic Free Jet of Combustion Gases using Two-Line OH Fluorescence," *App. Optics* **35**, 485-499 (1996).
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19. S.I. Chou, D.S. Baer and R.K. Hanson, "Diode-Laser Absorption Measurements of CH_3Cl and CH_4 near 1.65 μm ," *Appl. Optics*, **36**, 3288-3293 (1997).
20. M.C. Thurber, F. Grisch and R.K. Hanson, "Temperature Imaging with Single- and Dual-Wavelength Acetone Planar Laser-Induced Fluorescence," *Opt. Lett.*, **22**, 251-253 (1997).
21. R.M. Mihalcea, D.S. Baer and R.K. Hanson, "Diode-Laser Sensor for Measurements of CO , CO_2 and CH_4 in Combustion Flows," *App. Optics* **36**, 8745-8752 (1997).
22. V. Nagali, S.I. Chou, D.S. Baer and R.K. Hanson, "Diode-Laser Measurements of Temperature-Dependent Collision Widths of H_2O Transitions in the 1.4 μm Region," *J. Quant. Spectrosc. Radiat. Transfer* **57**, 795-809 (1997).
23. R.J. Cedolin, W.A. Hargus Jr., P.V. Storm, R.K. Hanson and M.A. Cappelli, "Laser-Induced Fluorescence Study of a Xenon Hall Thruster," *App. Phys. B*, **65**, 459-469 (1997).
24. V. Nagali and R.K. Hanson, "Design of a Diode-laser Sensor to Monitor Water Vapor in High-Pressure Combustion Gases," *Applied Optics*, submitted April, 1997.
25. M.C. Thurber, F. Grisch, B.J. Kirby, M. Votsmeier and R.K. Hanson, "Measurement and Modeling of Acetone Laser-Induced Fluorescence with Implications for Temperature Imaging Diagnostics," *App. Optics*, submitted 9/97.

26. F. Grisch, M.C. Thurber and R.K. Hanson, "Mesure de Température par Fluorescence Induite par Laser sur la Moléculaire d'Acétone," *Revue Scientifique et Technique de la Défense* **4**, 51-60 (1997).
27. R.M. Mihalcea, D.S. Baer and R.K. Hanson, "Diode-Laser Absorption Sensor System for Combustion Emission Measurements," *J. Measurement Science and Technology*, in press.
28. R.M. Mihalcea, D.S. Baer, and R.K. Hanson, "Tunable Diode-Laser Absorption Measurements of NO₂ near 670 and 395 nm," *App. Opt.* **35**, 4059-4064 (1996).

3.2 Presentations and Technical Reports (11/94 – 10/97)

1. D.S. Baer, V. Nagali, E.R. Furlong, R.K. Hanson and M.E. Newfield, "Scanned- and Fixed-Wavelength Absorption Diagnostics for Combustion Measurements using Multiplexed Diode-Laser Sensor System," AIAA-95-0426 at 33rd AIAA Aerospace Sciences Meeting, Reno, NV, Jan. 9-12, 1995.
2. N.J. Brock, M.S. Brown, P.A. DeBarber, M.C. Thurber, S. Wehe and R.K. Hanson, "Hydroxyl Concentration Measurements in Shock-Heated Flows Using Resonant Holographic Interferometric Spectroscopy (RHIS)," paper AIAA-95-1951 at AIAA 26th Plasmadynamics and Lasers Conference, San Diego, CA, July 1995.
3. R.J. Cedolin, R.K. Hanson and M.A. Cappelli, "LIF Lineshape Analysis of the Xenon $6s[3/2]_2^0 - 6p[3/2]_2$ and $6s[3/2]_1^0 - 6p[1/2]_0$ Transitions in a Glow Discharge," paper AIAA-95-1969 at AIAA 26th Plasmadynamics and Lasers Conference, San Diego, June 1995.
4. F. Grisch, M. Thurber and R.K. Hanson, "Temperature Measurement by Acetone LIF with Dual-Wavelength Excitation," WSS/CI paper 95F-192, Stanford, CA, Oct. 30-31, 1995.
5. M. Kamel, C. Morris and R.K. Hanson, "Expansion Tube Studies of Hypersonic Reactive Flows around Projectiles," AIAA-95-0233 at 33rd AIAA Aerospace Sciences Meeting, Reno, NV, Jan. 9-12, 1995.
6. C. Morris, M. Kamel, M. Thurber, S. Wehe and R.K. Hanson, "Expansion Tube Investigation of Combustion Structures in Supersonic Projectile Flowfields," presented at 20th Intl. Symp. on Shock Waves, Pasadena, July 1995.
7. C. Morris, M. Kamel, M. Thurber, S. Wehe and R.K. Hanson, "Development of an Expansion Tube for Investigation of Combustion in Supersonic Projectile Flowfields," paper AIAA-95-2717 at 31st AIAA Joint Propulsion Conference, San Diego, July 10-12, 1995.
8. C. Morris, M. Kamel, M. Thurber, S. Wehe and R.K. Hanson, "Development of an Expansion Tube for Investigation of Combustion in Supersonic Projectile Flowfields," presented at RAMACII, 2nd Int. Meeting on Ram Accelerators, Seattle, July 17-20, 1995.
9. V. Nagali, T. Furlong, S.I. Chou, R.M. Mihalcea, D.S. Baer and R.K. Hanson, "Diode-Laser Sensor System for Multi-Species and Multi-Parameter Measurements in Combustion Flows," paper AIAA-95-2684 at 31st AIAA Joint Propulsion Conference, San Diego, July 10-12, 1995.
10. V. Nagali, E.R. Furlong, S.I. Chou, R.M. Mihalcea, D.S. Baer and R.K. Hanson, "Diode-Laser Sensor System for Methane, Water and Temperature Measurements in Combustion Environments," WSS/CI paper 95F-195, Stanford, CA, Oct. 30-31, 1995.
11. D.S. Baer, R. Mihalcea and R.K. Hanson, "Multiplexed Diode-Laser Absorption Sensors for Combustion Monitoring," SPIE 1996 Int. Symp. on Optical Sensing for Environment and Process Monitoring, Dallas, Nov. 6-8, 1996.

12. R.J. Cedolin, R.K. Hanson and M.A. Cappelli, "Laser-Induced Fluorescence Diagnostics for Xenon Hall Thrusters," paper AIAA-96-2986 at 32nd AIAA/ASME/SAE/ASEE Joint Prop. Conf., Lake Buena Vista, FL, July 1-3, 1996
13. D.F. Davidson, E.L. Petersen, M. Röhrig, R.K. Hanson and C.T. Bowman, "Measurement of the Rate Coefficient of $H + O_2 (+M) \rightarrow HO_2 (+M)$ for $M = Ar$ and N_2 at High Pressures," 26th Symposium (International) on Combustion.
14. E.R. Furlong, D.S. Baer, and R.K. Hanson, "Combustion Control Using an Advanced Multiplexed Diode-Laser Sensor System," paper 96F-081 at WSS/CI Fall Meeting, Los Angeles, October 28-29, 1996.
15. E.R. Furlong, V. Nagali, D.S. Baer and R.K. Hanson, "Combustion Control using a Multiplexed Diode-Laser Sensor System," paper AIAA-96-0756 at the 34th Aerospace Sciences Meeting, Reno, Jan. 1996.
16. E.R. Furlong, D.S. Baer, M. Webber and R.K. Hanson, "Combustion Diagnostics and Control using a Multiplexed Diode Laser System," paper AIAA-96-2763 at 32nd AIAA Joint Prop. Conf., Lake Buena Vista, FL, July 1996.
17. E.R. Furlong, D.S. Baer, and R.K. Hanson, "Combustion Control Using an Advanced Multiplexed Diode-Laser Sensor System," 33rd JANNAF Combustion Meeting, Monterey, November 4-8, 1996.
18. A.F.P. Houwing, M.C. Thurber, S.D. Wehe, M. Kamel, C. Morris and R.K. Hanson, "PLIF Imaging and Thermometry of NO/N_2 Shock Layer Flows in an Expansion Tube," paper AIAA-96-0537 at the 34th Aerospace Sciences Meeting, Reno, Jan. 1996.
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20. Morris, M. Kamel and R.K. Hanson, "NO PLIF Imaging of Supersonic Reactive Flows Around Projectiles in an Expansion Tube," paper AIAA-96-0855 at the 34th Aerospace Sciences Meeting, Reno, Jan. 1996.
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23. S.H. Smith, E. Hasselbrink, M. Mungal and R. Hanson, "The Scalar Concentration Field of the Axisymmetric Jet in Cross-Flow," paper AIAA-96-01298 at 34th Aerospace Sciences Meeting, Reno, Jan. 1996.

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26. E.L. Petersen, R. Bates, D.F. Davidson and R.K. Hanson, "Laser Absorption and Infrared Emission Measurements in a High-Pressure Shock Tube," paper AIAA-97-0316 at AIAA 35th Aerospace Sciences Meeting, Reno, Jan. 6-9, 1997.
27. E.L. Petersen, R.W. Bates, D.F. Davidson, and R.K. Hanson, "Development of Laser-Absorption Techniques for Shock Tube Studies at Elevated Pressures," 21st Int'l. Symp. on Shock Tubes and Waves, July 20-25, 1997, Australia.
28. E.R. Furlong, R.M. Mihalcea, M. Webber, D.S. Baer and R.K. Hanson, "Combustion Sensing and Control using Wavelength-Multiplexed Diode-Lasers," paper AIAA-97-0320 at AIAA 35th Aerospace Sciences Meeting, Reno, Jan. 6-9, 1997.
29. E.R. Furlong, D.S. Baer and R.K. Hanson, "Control of Temperature and CO using Wavelength-Multiplexed Diode-Lasers," Proc. Of SPIE, Vol. 3172, paper 33; presented at 42nd annual SPIE meeting, San Diego, July, 1997.
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31. M. C. Thurber, B.J. Kirby, F. Grisch and R. K. Hanson, "Instantaneous Temperature Imaging with Single-Wavelength Acetone PLIF," paper AIAA-97-0151 at AIAA 35th Aerospace Sciences Meeting, Reno, Jan. 6-9, 1997.
32. R.K. Hanson, "Recent Advances in Laser-Based Combustion Diagnostics," paper AIAA-97-0115 at AIAA 35th Aerospace Sciences Meeting, Reno, Jan. 6-9, 1997.
33. R.M. Mihalcea, D.S. Baer and R.K. Hanson, "Multiplexed Diode Laser Absorption Sensor System for Measurements of Combustion Pollutants," Proc. Of SPIE, Vol. 3172, paper 10, presented at 42nd annual SPIE Meeting, San Diego, July, 1997.
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35. R.K. Hanson, "Advanced Laser-Based Diagnostics for Shock Tube/Tunnel Flows," plenary paper, 21st Int'l. Symp. on Shock Tubes and Waves, July 20-25, 1997, Australia.
36. R.M. Mihalcea, D.S. Baer and R.K. Hanson, "Diode-Laser Absorption Sensor System for Combustion Monitoring and Control Applications," paper AIAA 97-3356 at 33rd Joint Propulsion Conference, July 7-9, 1997, Seattle, WA.

4.0 PERSONNEL

Individual researchers supported by the program are listed below. All the work has been carried out in the High Temperature Gasdynamic Laboratory, in the Department of Mechanical Engineering, under the supervision of Professor R. K. Hanson.

4.1 Postdoctoral Research Associates

Dr. D.S. Baer

4.2 Graduate Research Assistants

Students supported partially or fully during the period of this grant:

Renato Cedolin (50% time)

Andrew Chang (50% time)

Paul Danehy

Ted Furlong

Venu Nagali

Jennifer Palmer

Mark Thurber

Shang-I Chou

Radu Mihalcea

4.3 Ph.D. Degrees Awarded (1995-1997)

Dr. Paul Danehy, 6/95, "Population- and Thermal-Grating Contributions to Degenerate Four-Wave Mixing"

Dr. Michael DiRosa, 5/96, "High-Resolution Line Shape Spectroscopy of Transitions in the Gamma Bands of Nitric Oxide"

Dr. Renato Cedolin, 6/97, "Laser-Induced Fluorescence Diagnostics of Xenon Plasmas"

Dr. Jennifer Palmer, 8/97, "Temporally Resolved Velocimetry in a Shock-Tunnel Free Jet by Planar Fluorescence Imaging of Nitric Oxide"

5.0 SIGNIFICANT INTERACTIONS

In addition to the interactions associated with the presentations and publications listed in Section 3, we have had numerous visitors to our laboratory during the past three years. Foreign visitors have come from Germany, France, Great Britain, Canada, Spain, Finland and Japan; industrial and national laboratory visitors have included representatives from Rocketdyne, Aerometrics, Physical Sciences, Inc., Boeing, Metrolaser, AEDC, NASA Ames, NASA Lewis, Sandia, Lawrence Livermore, General Motors, Nissan, Hitachi, Kao Corporation and Toyota. Professor Hanson has given invited presentations on AFOSR-sponsored diagnostics research to several industrial laboratories, universities, and government groups in the U.S., Europe and Japan. Members of our group have provided technical information and advice, by telephone and mail, to several external researchers interested in duplicating or extending our diagnostics concepts.

Interest in the potential application of advanced laser diagnostic techniques developed at Stanford to various practical problems continues at a high level, and several notable transitions have been accomplished. During the past four years, we have collaborated with researchers at NASA-Ames to implement our diode laser diagnostics schemes in their 16-inch shock tunnel test program on advanced scramjet combustors; and we have engaged in a series of collaborative projects with Metrolaser to apply and transfer Stanford's expertise with PLIF imaging and diode laser absorption. For example, Metrolaser now markets a dual-camera PLIF system developed at Stanford. Another company, PSI, has hired three recent Ph.D. graduates of our High Temperature Gasdynamics Lab as part of their growing effort to develop and apply laser diagnostics, much of which is based on techniques pioneered at Stanford. The use of acetone as a flow tracer for PLIF imaging, a concept developed at Stanford, has quickly been adopted by research groups in the U.S., Europe and Japan, including researchers at AF Wright Labs. Finally, we have collaborated during the last year of this program with researchers at NAWC to implement diode laser-based sensors for near-real-time combustor control.

6.0 INVENTIONS

None.